APPENDIX   B

SENSITIVITY ANALYSIS OF COMPOSITE LINER
LEAKAGE RATES

B.1   INTRODUCTION

An implicit assumption in the analysis of leakage from various liners as presented in this *Guidance* is that liner performance does not change with time; i.e., leakage through a particular liner system remains constant throughout the 10,000-yr period of performance. Also implicit in the analysis of leakage is the assumption that the nature of quality control during installation results in minimal defects in the liner system. In order to initiate an understanding of how the leakage rate may change with time as the liner degrades, and to account for the "less-than-perfect" liner, this sensitivity analysis was undertaken to evaluate how the number and size of defects in a geomembrane affect the leakage rate of industrial waste leachate from a landfill through a composite liner. As outlined in Section 4.1 of the Technical Background Document, the infiltration rates to the unsaturated zone as a result of leakage from waste management units (WMU) through native soil, a single clay liner, and a composite liner were determined by three different methods. The assumptions for calculating leakage from the three liner-types are outlined in Tables 4-1 to 4-3 and summarized below.

The infiltration rates for the no-liner scenario were calculated with the HELP model (Schroeder et al., 1994) for a range of soil types and a range of precipitation rates that are representative of rates throughout the United States. The no-liner infiltration rate is effectively the same as percolation through the native soil. Because soil type and precipitation rates vary across the nation, the infiltration rates into the unsaturated zone from a landfill range from 1×10^{-5} m/yr to 1.08 m/yr.

Single-liner infiltration rates were calculated with the HELP model (Schroeder et al., 1994), based upon Darcy's law, using a range of precipitation rates from across the United States. Similar to the no-liner scenario, a range of infiltration rates to the unsaturated zone was determined: 0.0 m/yr to 0.53 m/yr for landfills.

The composite-liner leakage rate was calculated as a single value, using an equation from Bonaparte et al. (1989); assuming a constant 1-ft hydraulic head and three feet of low-permeability (10^{-9} m/s hydraulic conductivity) soil underlying the geomembrane.

Because the analyses of the no-liner and single-liner scenarios are based upon a range of infiltrations rates, the question was raised concerning why a single infiltration/leakage rate was used for evaluation of the composite liner scenario. The singular value for the composite liner is presented in the Guidance as a design and performance goal. This sensitivity analysis is based upon the recognition that a range of performance values might be expected. However, in order to assess what that range might be, there is a need to first evaluate how the type, number, and size of defects, the hydraulic head, and the effectiveness of the underlying low-permeability soil beneath the geomembrane affect the infiltration to the unsaturated zone.

This analysis illustrates that the hydraulic head and the contact between the geomembrane and the underlying clay, have a significant effect on the rate of leakage through a composite liner.

B.2   COMPOSITE LINER LEAKAGE RATE DETERMINATION

The equations used to calculate the leakage from a waste management unit (WMU) through a composite liner depend on the type of defect and the contact between the geomembrane material and the underlying low-permeability soil. The equations used in this analysis were empirically derived by Bonaparte, Giroud and others (1989, 1992). The following discussion outlines the equations and the assumptions used in this analysis.

B.2.1   EVALUATION OF LEAKAGE THROUGH HOLES

Bonaparte et al. (1989) described the leakage rate through a single hole in the geomembrane as:

$$Q = 0.21 \ a^{0.1} \ h^{0.9} \ k_s^{0.74} \tag{1}$$

where

- Q = steady-state flux from one hole in the geomembrane component of a composite liner (m^3/s);
- a = area of hole (m^2);
- h = head of liquid on geomembrane (m);
- k_s = hydraulic conductivity of the low-permeability soil underlying the geomembrane (m/s).

Equation (1) computes leachate flux through a hole in the geomembrane for which there is good contact between the geomembrane and the underlying low-permeability soil. Similarly, if there is poor contact between the geomembrane material and the low-permeability soil, the flux may be described as:

$$Q = 1.15 \ a^{0.1} \ h^{0.9} \ k_s 0.74 \tag{2}$$

Two equations were developed by Giroud and Bonaparte (1989) to estimate the leakage through a single hole in a geomembrane with perfect contact between the synthetic and natural materials.

Giroud and Bonaparte (1989) described the leakage as:

$$Q' \ p @ k_S @ d @ h_W /(1 \& 0.5 @ d / H_s) \tag{3}$$

where

Q = leakage rate (m^3/s);
k_s = hydraulic conductivity of the low-permeability soil (m/s);
d = diameter of the circular hole (m);
h_w = head of liquid on top of the geomembrane (m);
H_s = thickness of the low-permeability soil (m).

Because the ratio of the size of the hole to the thickness of the low-permeability soil layer is small,

$$1 \& 0.5 @ d/H_s . 1$$

equation (3) reduces to:

$$Q' \ p @ d @ h_W @ k_S \tag{4}$$

The leakage rate from a composite liner used in developing the Guidance was determined with equation (1). The parameter values used are listed below:

• one hole per acre;
• 0.05 in^2 hole (3E-06 m^2);
• 1 ft head (0.305 m) for landfills and waste piles; 10-ft head for surface impoundments;
• under-lying clay layer with 10^{-9} m/s hydraulic conductivity.

Using these parameter values, the leakage rate used in the Industrial Waste Guidance groundwater analysis is 3.41 x 10^{-5} m/yr for landfills and waste piles; 3.1 x 10^{-4} m/yr for surface impoundments.

Bonaparte et al. (1989) stated that the use of the above empirically-based equations should be restricted to cases where the underlying low-permeability soil has hydraulic conductivity less than 10^{-6} m/s; and the head of liquid on top of geomembrane is less than thickness of underlying low-permeability soil. It should also be emphasized that the above equations describe leakage through a single defect. In addition to evaluating the sensitivity of leakage through a single hole, this sensitivity analysis also considered the effects of 1000 holes per acre.

B.2.2 Evaluation of Linear Defects

The following four equations were developed by Giroud and Badu-Tweneboah (1992) to estimate the leakage through long defects in a geomembrane. This analysis considered two lengths of long defects (i.e., tears): 1-m and 63-m. A roll of geomembrane material is approximately 63 m long and this length was considered analogous to the infinitely long defect described by Giroud and Badu-Tweneboah (1992).

Leakage through a 1-m tear where there are good contact conditions was determined with:

$$Q = 0.52 \cdot i^{(}_{ave} \cdot (B \& b) \cdot b^{0.1} \cdot h_W^{0.45} \cdot k_S^{0.87} \% 0.21 \cdot i_{ave} \cdot b^{0.2} \cdot h_W^{0.9} \cdot k_S^{0.74} \tag{5}$$

where:

Q	=	rate of leakage through a tear in the geomembrane component of the composite liner (m^3/s);
B	=	geomembrane tear length (m);
b	=	geomembrane tear width (m);
h_W	=	head of liquid on top of the geomembrane (m);
k_S	=	hydraulic conductivity of the low-permeability soil component of the composite liner (m/s);
i^*_{ave}	=	average hydraulic gradient beneath the rectangular portion of the wetted area;
i_{ave}	=	average hydraulic gradient of soil beneath the circular portion of the wetted area.

i^*_{ave} and i_{ave} are described by Giroud and Badu-Tweneboah (1992) in terms of the radius of the wetted area (R) and the thickness of the low-permeability soil, H_s:

$$i_{ave} = 1 \% h_w / [2 \cdot H_s \cdot \ln(2 \cdot R / b)] \tag{6}$$

$$i^{(}_{ave} = 1 \% h_w / [H_s \cdot \ln(2 \cdot R / b)] \tag{7}$$

The radius of the wetted area may be determined with Equations (8) and (9) for good and poor

contact conditions:

$$R' \; 0.26 \text{\@} b^{0.1} \text{\@} h_W^{0.45} \text{\@} k_S^{\&0.13} \tag{8}$$

Similarly, the leakage through a linear defect for which there is poor contact between the geomembrane and low-permeability soil is described as:

$$Q' \; 1.22 \text{\@} i_{ave}^{(} \text{\@}(B\&b) \text{\@} b^{0.1} \text{\@} h_W^{0.45} \text{\@} k_S^{0.87} \% 1.15 \text{\@} i_{ave} \text{\@} b^{0.2} \text{\@} h_W^{0.9} \text{\@} k_S^{0.74} \tag{9}$$

where:

$$R' \; 0.61 \text{\@} b^{0.1} \text{\@} h_W^{0.45} \text{\@} k_S^{\&0.13} \tag{10}$$

Leakage through tears of infinite length for good contact conditions is described as:

$$Q(' \; 0.52 \text{\@} i_{ave}^{(} \text{\@} b^{0.1} \text{\@} h_W^{0.45} \text{\@} k_S^{0.87} \tag{11}$$

and for poor contact conditions

$$Q(' \; 1.22 \text{\@} i_{ave}^{(} \text{\@} b^{0.1} \text{\@} h_W^{0.45} \text{\@} k_S^{0.87} \tag{12}$$

where: $Q^* $ = rate of leakage per unit length of the tear;
$i_{ave}^{\;*}$ = hydraulic gradient beneath the rectangular portion of the wetted area.

B.3   THE APPROACH

The objective of this sensitivity analysis was to determine whether there is a range of leakage rates given various defects in liners. Consequently, the analysis focused on properties of the defects rather than on the overall design of the liner system. The parameters and the values used in this analysis are listed in Table B-1. All possible combinations of each of the parameters were determined using Equations (1) - (4) for notes and Euqations (5) - (12) for rips/tears.

Table B.1   Parameters for Composite Liner Infiltration Sensitivity

Defect/ Equations Used	Defect Size	Density	FML/Clay Contact	Clay Conductivity	Head
Hole (1)-(4)	0.0001 m^2 0.00003 m^2	1 per acre 1000 per acre	poor good perfect	1E-06 m/s 1E-09 m/s	3.05E-01 m 3.05 m
Rip/tear (5)-(12)	1 m infinitely long (63 m)[a] width: 0.01 m 0.03 m	1 per acre 10 per acre[b]	poor good	1E-06 m/s 1E-09 m/s	3.05E-01 m 3.05 m

[a] approximate length of roll of geomembrane material
[b] number of widths of geomembrane per acre

B.4   RESULTS

The steady-state leakage rates calculated using Equations (1) - (12) assume dimensions for defects in the geomembrane that range over many orders of magnitude. Specifically, the minimum and maximum values for leakage through a hole are 1.5×10^{-8} m/yr to 353 m/yr, respectively. The minimum and maximum leakage rates through a linear defect are 7.45×10^{-5} m/yr to 67.4 m/yr, respectively. These rates overlap with the ranges observed for the no-liner and single-liner scenarios described earlier.

B.4.1 Leakage Through Holes

Figure B-1 presents the results for the case of leakage through holes in the geomembrane. The leakage rates through a single hole with 1-ft hydraulic head are less than the leakage through a 3-ft layer of clay with a hydraulic conductivity of 10^{-7} cm/s for all contacts and both hole sizes. The leakage rates for the single-clay liners, as determined with Darcy's law, are given for comparison. When there are 1000 holes per acres and a 1-ft hydraulic head, leakage through the geomembrane with poor contact exceeds that of the clay. When there is a 10-ft head of liquid on the geomembrane, leakage through the geomembrane with good and poor contact and 1000 holes per acre exceeds that of the clay liner. These latter results appear to be counter-intuitive because they suggest that the clay and geomembrane, together, do not perform as well as the single-clay liner.
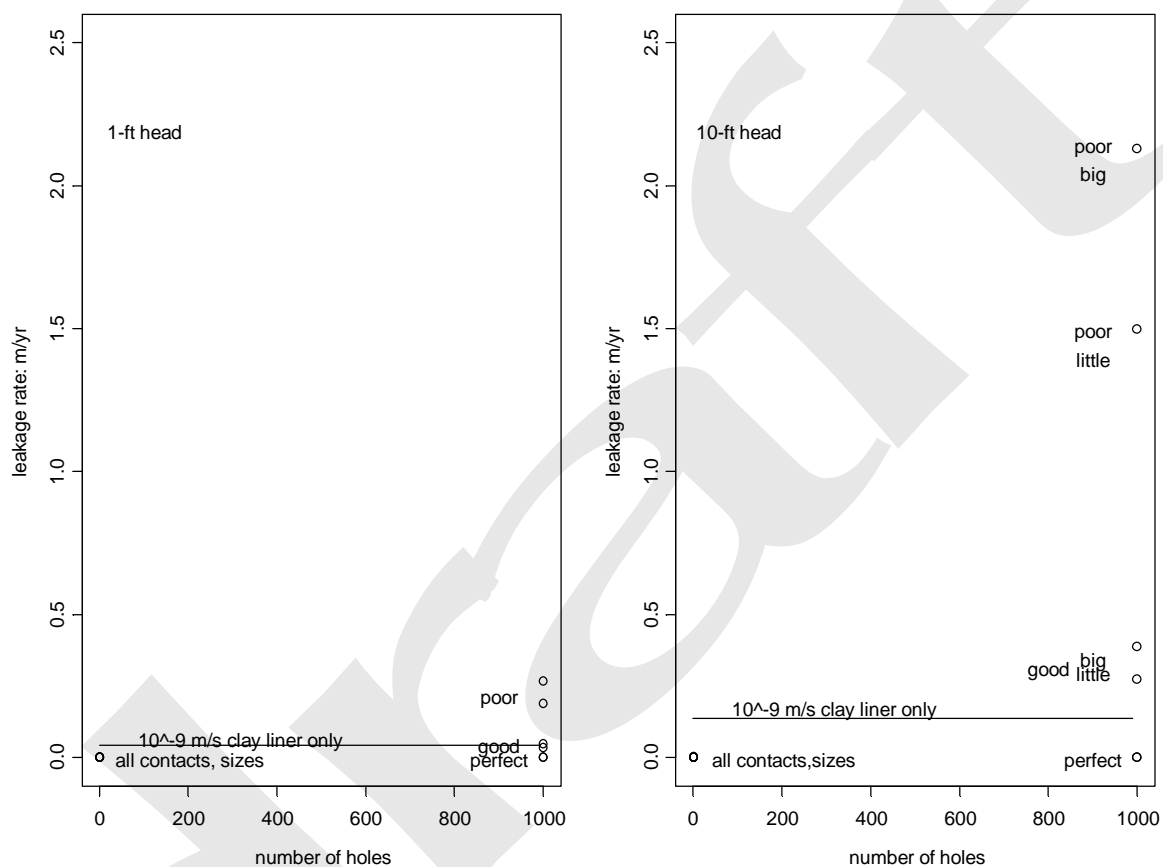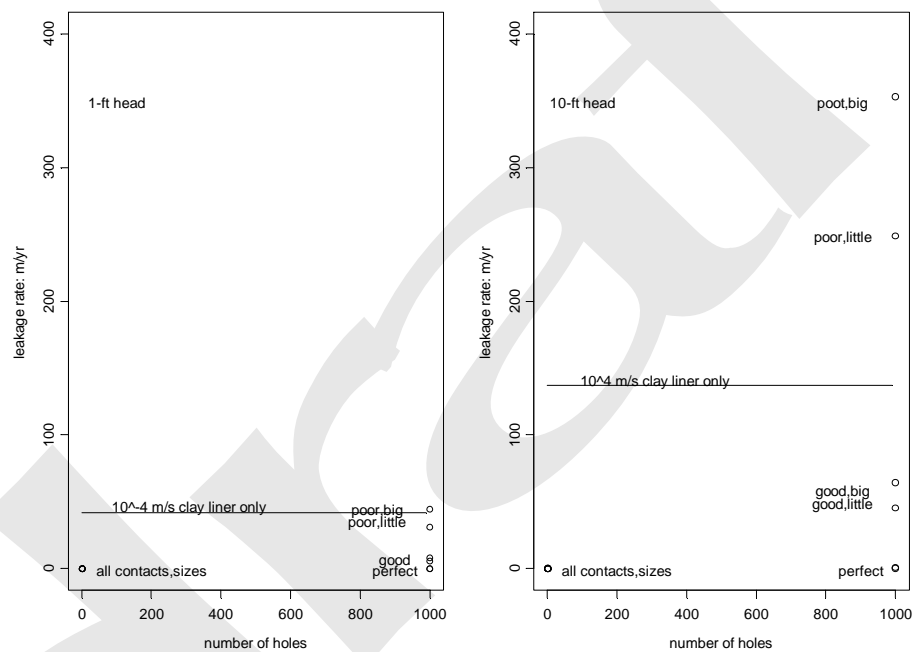
Figure B-1. **Leakage Rates from a Composite Liner with Holes: 10^{-9} m/s Hydraulic Conductivity Clay** (geomembrane-clay contact quality denoted as poor, good, and perfect; "big" holes have an area of 1×10^{-4} m^2 and "little" holes have an area of 3×10^{-6} m^2).

Figure B-2 presents the results for leakage through holes in the geomembrane with an underlying clay of 10^{-4} cm/s hydraulic conductivity.   With the exception of the "poor" contact values, the 10-ft head leakage rates indicate that the geomembrane and clay perform at least as well as the clay itself. Of note are the high leakage rates (>100 m/yr) for the clay when there is a 10-ft head.

Figure B-2.   Leakage Rates from a Composite Liner with Holes: 10^{-6} m/s Hydraulic Conductivity Clay (geomembrane-clay contact quality denoted as poor, good, and perfect; "big" holes have an area of 1×10^{-4} m^2 and "little" holes have an area of 3×10^{-6} m^2).

### B.4.2   Leakage Through Linear Defects

Leakage through the composite liner when the geomembrane exhibits tears or rips is presented in Figures B-3 and B-4. With the exception of the 10 tears with poor contact conditions and a 10-ft hydraulic head, the leakage rates from the defective geomembrane are less than those from the underlying clays with permeabilities of 10^{-4} cm/s and 10^{-7} cm/s. These figures suggest that even with defects, the geomembrane affords more protection than the clay liner alone.

One result of note: when there are many defects, the holes generally leak more than the tears. Figure B-5 illustrates how 1000 holes and a 1-ft hydraulic head have a higher leakage rate than 10 63-m tears.   The area covered by 10 1-m rips of 0.03 m width is 0.3 m^2, whereas the area of 1000 3×10^{-6} m^2 holes is 0.003 m^2.   The tears would be expected to leak more than the holes because the defect has more area. The result presented in Figure 5 is counter-intuitive.

Giroud and Badu-Tweneboah noted that for large hydraulic head, it takes fewer holes to approximate the same wetted area as the tear, than when there is a small hydraulic head. Perhaps this effect is due to fluids spreading laterally between the geomembrane and the underlying clay: while the actual area of the defect represented by the holes is smaller than that of the tears, the affected/wetted area beneath the geomembrane is actually bigger for many small holes than for a single tear.
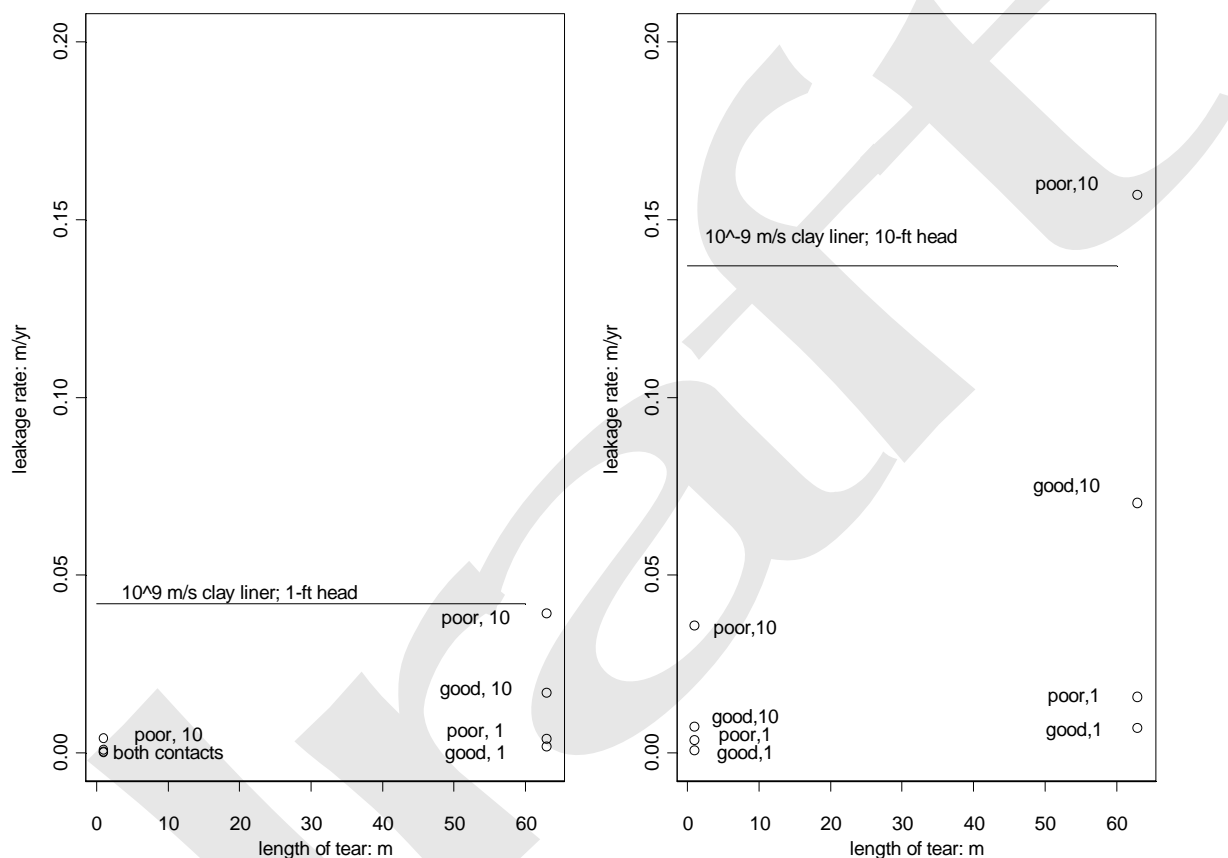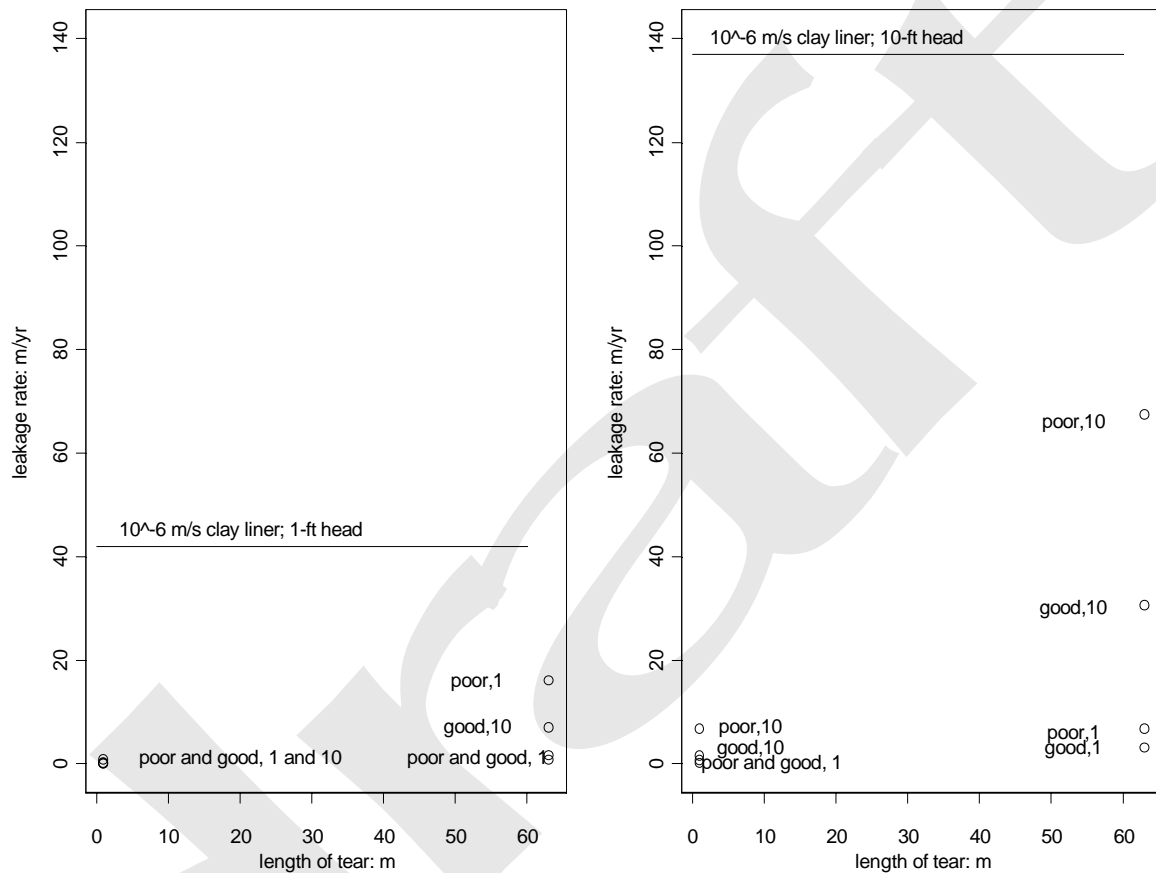
Figure B-3. **Leakage from Linear Defects in a Composite Liner: 10^{-9} m/s Hydraulic Conductivity Clay** (geomembrane contact quality denoted as good and poor; number of linear defects per acre noted as 1 and 10).
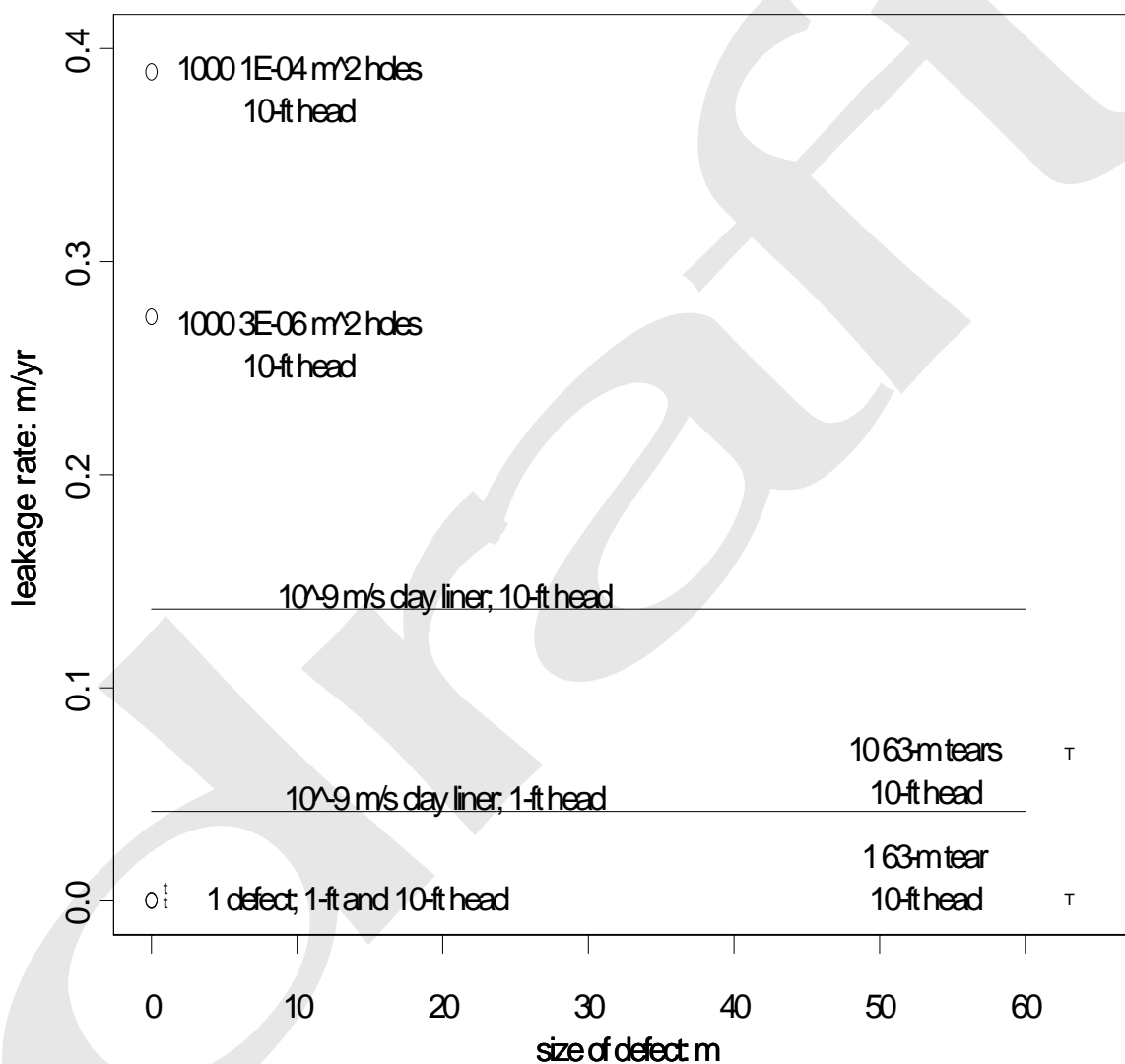
Figure B-4. **Leakage from Linear Defects in a Composite Liner: 10⁻⁶ m/s Hydraulic Conductivity Clay** (geomembrane contact quality denoted as good and poor; number of linear defects per acre noted as 1 and 10).

Figure B-5. **Summary of Leakage Rates from a Composite Liner with Good Geomembrane-Clay Contact** (holes noted as "O"; 1-m tears and 63-m tears noted at "t" and "T", respectively).

B.5   DISCUSSION

The results of this sensitivity analysis of composite liner leakage rates are presented in comparison to the leakage through a 3-foot clay layer with hydraulic conductivities of 10^{-9} m/s and 10^{-6} m/s. The leakage of a single clay liner can expected to be the limiting condition for the leakage, since the clay and geomembrane together should afford a higher level of protection than the clay liner alone. In general, the infiltration rates do not exceed the limiting leakage rate for the underlying clay except when there is poor contact and the hydraulic head is high.

There is an exception to this general conclusion: leakage from 1000 holes per acre, 10^{-9} m/s clay, good contact, and 10-ft hydraulic head also exceeds that of the clay alone. This result calls into question the validity of the equation for high heads or a large number of defects.

The equations presented by Bonaparte, Giroud and others (1989, 1992) are based on one defect. The equations do not take into account interaction of leakage from many defects. It was mentioned above that these authors caveated the use of the equations such that their application should be limited to those cases where the hydraulic head on top of the geomembrane is less than the thickness of the underlying low-permeability material. The results for the 10-ft hydraulic head on top of the good contact and poor contact liner with 1000 holes per acre support the validity of the Bonaparte and others' caveat: the equation for flow through holes is valid when the hydraulic head is less than the thickness of the underlying clay. The results also highlight the issue of how to determine leakage through composite liners for which the conditions defined by Bonaparte et al. are not appropriate.

There are circumstances considered in the design of this sensitivity analysis which implicitly require parameter values outside the range of values defined by Bonaparte et al. Specifically, it is doubtful that a geomembrane would have only one hole per acre. Surface impoundments often have hydraulic heads several fold greater than the thickness of the underlying clay. There are also conceivable circumstances for which the hydraulic conductivity of the underlying clay exceeds 10^{-6} m/s; e.g., when the clay has saturated with organics, or desiccates.

The leakage rates calculated in this analysis range over many orders of magnitude. If modeling of leakage from a composite liner were to be done in a Monte Carlo fashion with a range of values, the criteria for defining a conceivable range leakage rates must be considered. For leakage rates in excess of 10 m/yr, there is the need to consider whether such a leakage rate could be maintained.

The Florida Department of Environmental Protection studied the performance of 24 active

double-lined landfill cells for the purpose of comparing predicted leakage rates with actual leakage rates through the liner components (Teller, 1997). The observed leakage rates were generally less than those predicted using equations from Bonaparte et al. (1989). The observed leakage through a primary liner that consisted of a 60 mil HDPE membrane ranged from 5×10^{-4} m/yr to 0.2 m/yr. Leakage through the HDPE membrane and a geosynthetic clay liner with hydraulic conductivity of 2×10^{-9} cm/s ranged from 7×10^{-7} m/yr to 5×10^{-5} m/yr. Given these leakage rates, an HDPE liner underlain by a clay liner with hydraulic conductivity of 10^{-7} cm/s might exhibit a leakage rate on the order of 10^{-5} m/yr to 10^{-2} m/yr. The leakage rate assumed for the composite liner in development of the *Guidance* (3×10^{-5} m/yr) is at the low end of this range.

The leakage rates for the various liner scenarios used in developing the *Guidance* do not account for time-dependent changes in liner competence. The analysis presented here only assumes the existence of the defects. It does not allow for the development of defects as a function of stress due to loading, chaotic events such as earthquakes, or chemical interactions with the waste. There have been many studies of the effects of various stresses on the competence of geomembrane liner materials. Further work is needed to evaluate how liner systems degrade with time and the effect of such on leakage rates.

The EPA welcomes comments concerning the use of the Bonaparte and Giroud equations for estimating leakge through a composite liner. The Agency is also interested in comments concerning the use of a single leakage rate or a set of leakage rates, such as those sampled for a Monte Carlo-style analysis, or specifically chosen to represent degradation of the liner system with time.

B.6   CONCLUSIONS

The results of a parametric sensitivity analysis indicate that the leakage rate used for the composite-liner scenario in the *Industrial Waste Guidance* is at the low end of the range of leakage rates determined in this analysis. This suggests that while the leakage rate of 3.4×10^{-5} m/yr is a good performance goal, it is not conservative in that is doesn't result in a higher estimated risk. Data from the Florida study indicate higher leakage rates with similar designs. The results of this analysis need to be evaluated in terms of which scenarios are plausible before a range of leakage rates can be defined for a Monte Carlo style analysis.

The leakage rates calculated in the course of this sensitivity analysis raise questions concerning the general applicability of the equations developed by Bonaparte, Giroud, and others. While these authors caveat the use of the equations to certain conditions, it is unlikely that these conditions would always exist, particularly a low hydraulic head in a surface impoundment.

Given the uncertainties associated with this analysis, there is a need to verify the equations with more data. In order to better define a range of leakage rates for through composite liners for the purpose of including the uncertainty associated with leakage rates in a Monte Carlo analysis of the composite liner scenario, there is a need to better understand the nature of defects in composite liners, how defects develop with time, and how leakage rates vary with time.

B.7   REFERENCES

Bonaparte, R., J.P. Giroud, B.A.Gross (1989). Rates of Leakage Through Landfill Liners; *Geosynthetics '89 Conference Proceedings*, vol. 2; pp. 18-29; Amer. Soc. Civil Eng.

Giroud, J.P., and K. Badu-Tweneboah (1992). Rate of Leakage Through a composite Liner Due to Geomembrane Defects; *Geotextiles and Geomembranes*, vol. 11, pp. 1-28.

Giroud, J.P., and R. Bonaparte (1989). Leakage through Liners constructed with Geomembranes– Part I. Geomembrane Liners; *Geotextiles and Geomembranes*, vol. 8, pp. 27-67.

Giroud, J.P., and R. Bonaparte (1992). Leakage through Liners constructed with Geomembranes– Part II. Composite Liners; *Geotextiles and Geomembranes*,vol. 8, pp. 71-111.

Shroeder, P.R., T.S. Dozier, P.A. Zappi, B.M. McEnroe, J.W. Sjostrom, and R.L. Peyton (1994). The Hydrologic Evaluation of Landfill Peformance (HELP) Model; EPA/600/R-94-168b.

Teller, R.B. (1997). Evaluating the Performance of Florida Double-lined Landfills; *Geosynthetics'97;* Conference Proceedings, vol. 1, pp. 425-438.